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A SEMI-FORMAL APPROACH TO STRUCTURE AND ACCESS KNOWLEDGE FOR MULTI-MATERIAL-DESIGN

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Abstract

In recent years multi-material-design has been of broad interest. There has been a great deal of literature on how multi-material-design has support realisation of lighter, cheaper products with lower impact to the environment. However, there has been no general approach to name the essential potentials of multi-material-design as a first guideline to support suitable use of the technologies. On the basis of an extensive literature survey, this paper proposes a method to systematically derive these potentials. Moreover, we found that these potentials, such as "reducing weight", "improving mechanical performance" or "easing manufacture and assembly" can serve to structure the design knowledge required for multi-material-design. Therefore, we propose a model to link the specific potentials to measures and guidelines to support decision-making and knowledge application. This structuring may lead to finding suitable design guidelines for specific development goals more quickly. This could accelerate product development and make the benefits of multi-material-design more transparent, which will promote the dissemination of multi-material-design in industry.

Keywords: Knowledge management, Design engineering, Design methodology

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1 INTRODUCTION

Multi-material-design has been of broad interest within the last two decades. There has been a great deal of literature on how multi-material-design has supported reducing the weight and costs and even the environmental impact without negative effects to the functional properties of components and assemblies. Since the benefits of multi-material-design result from the combination of different materials such as steel and thermoplasts within one component, there is an increasing need to support designers when first deciding to use multi-material-design and, secondly, designing the component itself. However, there has been no general approach summarising the mentioned benefits and potentials of multi-material-design up to now. On the one hand, this leads to limited applications within the industry since the required design knowledge is often not available for practitioner. On the other hand, the design knowledge provided is generally only focussing single potentials of multi-material-design like weight without taking into account the effects on further properties of the product or processes. Based on an extensive literature survey, this paper proposes a structured set of the main potentials of multi-material-design. Moreover, we found that these potentials, such as "reducing weight", "improving mechanical performance" or "easing manufacture and assembly", can serve to structure the design knowledge needed to apply multi-material-design. Therefore, we propose a method to provide specific design knowledge on different levels like general measures and design guidelines. Its structuring may lead to find suitable principle solutions and embodiments for specific development goals more quickly. Furthermore, the proposed method supports the goal setting within early stages of product development when analysing previous design and defining the focus of a new design task. Thus, it makes the benefits of multi-material-design more transparent, which will promote the dissemination of multi-material-design in industry. In the following sections, we introduce the understanding of multi-material-design and discuss existing approaches to gain, structure and provide design knowledge.

1.1 Understanding Multi-Material-Design

Multi-material-design represents a specific technology which is based on the combination of different materials within one component. The heterogeneous materials such as steel and thermoplasts are combined within the production process, using shaping or moulding technologies. Based on Nestler, multi-material-designs can be described on different levels (2014) as shown in Figure 1. On the top level (first level), materials of different categories such as metals, plastics, and composites are combined. The second level allows to combine materials of the same material category, for instance aluminium, steel and magnesium, among the category metal. The bottom level (third level) combines materials of the equal subcategories, e.g. different steel grades.

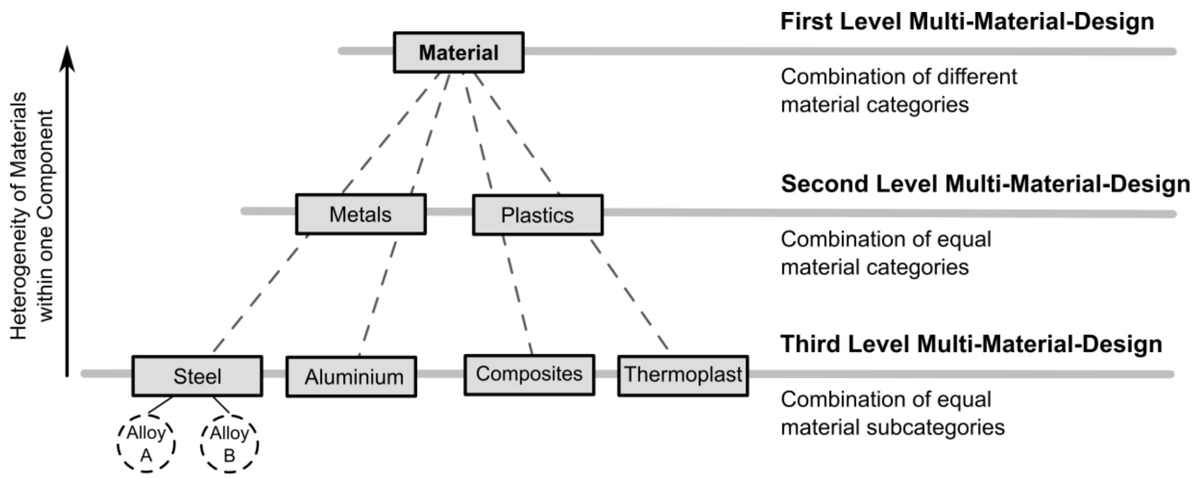

Figure 1. Level model of different Multi-Material-Designs

On the one hand, the higher the level of multi-material-design is, the higher are potential benefits such as weight reduction, since materials with the best fitting properties can be applied within one component. On the other hand, manufacturing and joining becomes more difficult. Third level multi-material-design is state-of-the-art in automotive engineering. Well established solutions are based on the combination of different steel grades for the automotive body-in-white. These different steel grades are easy to

manufacture, easy to join and show a good corrosion behaviour, which results in low production costs (Friedrich, 2013).
Second level multi-material-design is an advancing technology entering large scale production in automotive industry. The combination of different steel grades and aluminium is, for instance, used for the automotive body-in-white of upper-class vehicles c.f. (Mauer et al., 2014), (Seehafer, 2014). Most applications of level 2 are nowadays post-mould-assemblies. Already formed sheets of different materials are joined by adhesives and rivets in the bodyshop. Nevertheless, there are prototypes and pre-serial parts produced with in-mould-assembly. The technology VarioStruct represented some examples of shell and assembly parts, which consists of a steel body sheet with integrated or enveloped aluminium structure produced by casting. This production technology allows to join steel and aluminium directly during the casting process which leads to advantages like weight saving, higher stiffness, optimised deformation characteristics, efficient material use or acceleration of production speed (v. Kulmiz, 2012).
There is a first level multi-material-design in the automotive industry as well. In the early decade of serial parts, most first level applications were semi-structural parts, such as front-ends, mounting brackets or interior parts. Here, metal structures are used for load-bearing, while plastic structures are applied to carry attachment parts. In single applications, short or long fibre reinforced plastics are connected to the main metal structure by form closure or adhesives. The research presented in this paper focuses on the analysis of the potentials of first level multi-material-design. Therefore, different examples of already existing applications are given in section two.

1.2 Approaches and Challenges for Decision Making in Multi-Material-Design

Engineers require information from a variety of sources to support decision making during the design process. According to Blockley (1980), four types of information are available, namely national regulations and specifications, professional information, commercial and product information, experience from previous similar work and also site information. In order to make use of this information during the design process, it has to be provided timely, dependably, appropriately for issues at hand, and understandably (Nowack, 1997). In this work, we focus on the knowledge derived from previous similar works since the use of existing principle solutions, solution elements or embodiments is common practise in engineering design (Roth, 2002). This knowledge is often referred to as design guidelines c.f. (Krizan, 1995), (Bischoff, 2010), design principles c.f. (Wallace, 1999), (French, 1994) or solution principles e.g. (Inkermann, 2013). However, there is a challenge to access the design knowledge suitable for the design task at hand, since different levels of concretisation and detail as well as different properties of the system under development have to be addressed. With regard to multi-material-design and lightweight design aside from manufacturing issues aspects of material selection, embodiment design and topology optimization are in focus (Wiedemann, 2007). For instance, the method and tools proposed by Ashby support the selection of materials based on criteria such as type of load or specific key performance indicators formulated for the design task at hand (Asbhy et al., 2004), (Jahan et al., 2010). Moreover, specific approaches, especially for material selection in multi-material-design, have been defined by Giaccobi et al., (2010), where the material is selected for each function individually. General design guidelines like "Load-path-oriented Design" are described in a plenty of works like (Roth, 2000), (Pahl et al., 2007). Furthermore, there are different works dealing with the formulation of guidelines and principles to transfer embodiment design occurring in nature. Nehuis et al. propose different design catalogues to accelerate the development of new lightweight steel profiles. These design catalogues contain standardised components and features which can be easily integrated and design rules for lightweight design (Nehuis et al., 2011). The works mentioned here are differing widely concerning the details of information provided, the structure in which the knowledge is organised and objective the information is provided for. In order to support decision making in multi-material-design, three main findings have to be addressed by future work:

- There are no approaches which are providing strategic, problem-situated, and procedural knowledge for multi-material-design and the assignment of these different knowledge types.
- Today's methods are limited to two or three material selection criteria. Therefore, the heterogeneity of multi-material components is rather supported.
- The known guidelines and principles mainly focus on product properties but do not give references to benefits concerning the development or production process.

In particular, the lacking assignment of the different knowledge types and the limited view upon specific product properties hinder a holistic decision-making. This is why we derived the need to systematically identify potentials of multi-material design based on a literature survey. Thereafter, we want to use the derived potentials for structuring design guidelines. The findings mentioned serve as a hypothesis for our research on supporting multi-material-design in automotive industry and set the focus of our research.

1.3 Research Focus of this Contribution

Based on the understanding and analysis described above, our research aims at providing a methodology to support decision-making in multi-material-design in automotive context. Therefore, three questions are in the focus of our research:

- What are specific benefits and potentials of multi-material-design in automotive context and how can these be translated into strategic, problem-situated, and procedural knowledge?
- How can the different knowledge types be assigned to allow application and estimation of effects in different design stages?
- How can the knowledge be structured and presented to be useful for engineers in practice and exploit the potentials of multi-material-design?

Our preliminary research results presented here are based on the hypothesis that the required knowledge can be derived from existing solutions and applications of multi-material-design. Hence, the main part of the research is the analysis of existing solutions and the formulation of general potentials as well as specific design guidelines.

The paper is organised as follows. In section two the methodology used to derive the design knowledge and structure is described and exemplary components and their main properties are given. Section three introduces the proposed semi-formal model to structure knowledge for multi-material-design. In section four we highlight the structure and realisation of a manual for multi-material-design and the linking of the specific design guidelines to potentials and measures defined before. The paper closes with a discussion and conclusion.

2 METHODOLOGY TO DERIVE POTENTIALS AND DEISGN GUIDELINES FOR MULTI-MATERIAL-DESIGN

In most of the design processes, existing solutions are used (Hansen and Andreasen, 2002). The reuse of established solutions helps to reduce development time and risk, since main properties of the solution elements or embodiments are known or can be estimated with limited effort. In order to define the main potentials and derive design principles for multi-material-design, we conducted a literature review with focus on applications in the field of automotive. Table 1 represents an excerpt of the analysis. The components analysed are predominantly structural components like a B-Pillar, mounting parts like a frontend and flaps from past and current research and development projects. In order to highlight the potentials of upcoming multi-material-design, most parts can be classified as first level multi-material-design representing a combination of metal and plastic materials within one component. The components are either serial parts which have already been used in existing cars as well as pre-serial or research projects aiming to demonstrate specific technologies, without applying these parts in industry. Table 1 gives three examples of analysed components and gathers exemplary information. The analysis was structured by two overall questions:

- What are the objectives and reasons mentioned by the producers and researchers to use multi-material-design?
- How is the multi-material-design realised in the specific application?

The information to answer these questions was derived from descriptions provided in journals, press releases and on exhibitions of the producers or researchers. Therefore, we evaluated the readiness level of the components, the material combination used, the structure as well as the joining technologies within the component. This information characterises the solution itself and gives insight to derive problem situated and procedural knowledge to support multi-material-design. Aside from this solution-specific information, the main objectives and potentials of the projects and components were analysed. These potentials are, for instance, concerning product properties like weight or number of parts as well as process-related properties like assembly effort or manufacturing time. Within the review, we were only able to investigate the intended improvements without comprehend if these were actually realised in every case. However, this information provides knowledge on a more strategic level, addressing the question why to use multi-material-design.

Table 1. Example of 1st level multi-material-components analysed

Component	Frontend	B-Pillar	Roof Crossmember
Figure			
Readiness Level	Serial part. Audi A8	Pre-Serial part, Research TU Dresden	Serial part: Audi A6
Material Combination	Aluminium sheet metal PA6 GF30 Continuous filament organic sheet (glass fibre, PA6 matrix)	Steel sheet metal Glass LFT with PA matrix Continuous filament organic sheet metal (glass fibre, PA6 matrix)	Steel sheet metal PA6 GF30
Structure	Aluminium body sheet connected to the organic sheet lower belt with PA6 GF30 by injection moulding process	Steel body sheet reinforced with organic sheet and glass LFT with PA matrix by impact extrusion process	Steel body sheet reinforced with PA6 GF30 by injection moulding process
Joining Technology	Form closure In mould lamination	In mould lamination	Form closure In mould lamination
Main Potentials	-Weight reduction (-20%) on lower belt -Reduced assembly	- Weight reduction (-10%) at equal failure behaviour - One shot manufacturing process	- Weight reduction (-30%) at equal component costs - Reduction of components (one part less)
Reference	Lanxess, 2010	TU Dresden, 2016	Jäschke et al., 2004

Based on the analysis of 56 components, we derived the main potentials mentioned and clustered them into seven fields. The fields are allocated to both product and process properties and represent an aggregation of general benefits of multi-material-design on a strategic level. Furthermore, the analysis of the solutions themselves provides information about how to realise multi-material-design and therefore, can be understood as measures to achieve the potentials stated. In order to support the realisation of components based on multi-material-design, design guidelines were formulated with regard to the existing solutions.
The following sections will introduce the model and structure the different types of knowledge gathered by the analysis.

3 A SEMI-FORMAL MODEL TO STRUCTURE DESIGN KNOWLEDGE FOR MULTI-MATERIAL-DESIGN

As highlighted before, the support of decision-making and realisation of multi-material-design requires knowledge of different types. Based on the analysis described above, we therefore propose a semi-formal model to structure the design knowledge, differing between strategical, problems-situated and procedural knowledge (Nowack, 1997). The model recommends the structure and the content of the three knowledge levels as well as their connection. Table 2 provides a first overview of the first two levels which we call potentials and measures.
The potentials represent general fields of improvement which can be addressed by multi-material-design. These fields are, on the one hand, related to the product and the design like functions or design freedom. On the other hand, there are fields related to the design and production process like production or development effort and resource efficiency. The fields of potentials represent aggregations of general properties like proposed for instance by Pahl et al. (2007) or Hubka and Eder (1988).

Table 2. Excerpt of the potentials of multi-material-design and measures to achieve these (for complete list of measures, components and references please contact the authors)

No.	Potential	No.	Measure	Components	Reference(s)
1.	Improvement of properties and/ or functions	1.1	Improve local stiffness	Crossmember Crossmember Seat shell Rear bumper beam Mounting Bracket	Jäschke et al. 2004, v. Kulmiz 2012, Ehleben 2011, Lanxess 2016b, Lanxess 2014
		1.2	Improve local strength	Crossmember Crossmember Seat shell Rear bumper beam Mounting Bracket	Jäschke et al. 2004, v. Kulmiz 2012, Ehleben 2011, Lanxess 2016b, Lanxess 2014
2.	Advanced flexibility (product and/ or process)	2.1	Vary wall thicknesses	Crossmember Airbag housing TRB B-Pillar	Jäschke et al. 2004, Lanxess 2013, ErlingKlingler Muhr et al. 2015
		2.2	Vary material distribution	Crossmember Crossmember Airbag housing Mounting Bracket	Jäschke et al. 2004, v. Kulmiz 2012, Lanxess 2013, Lanxess 2014
3.	Reduced development effort	3.1	Reduce manufacturing restrictions	Roof	KraussMaffei 2016
		3.2	Reduce organisational interfaces	Crossmember Roof	Jäschke et al. 2004, KraussMaffei 2016
4.	Increased resource efficiency	4.1	Increase material efficacy	Crossmember Frontend Roof	Jäschke et al. 2004, Lanxess 2008, KraussMaffei 2016
		4.2	Reduce number of tool	Crossmember Crossmember	Jäschke et al. 2004, v. Kulmiz 2012
5.	Reduced production effort	5.1	Reduce productions steps	Crossmember Crossmember Brake pedal Rear bumper beam Mounting Bracket Crossmember	Jäschke et al. 2004, v. Kulmiz 2012, Lanxess 2016a, Lanxess 2016b, Lanxess 2014, ErlingKlingler 2015
		5.2	Reduce logistics and storage	Crossmember Crossmember Brake pedal Rear bumper beam	Jäschke et al. 2004, v. Kulmiz 2012, Lanxess 2016a, Lanxess 2016b
6.	Reduced intersections and assembly effort	6.1	Integration of components	Crossmember Crossmember Frontend Frontend	Jäschke et al. 2004, v. Kulmiz 2012, Lanxess 2010, Lanxess 2008
		6.2	Integration of joining elements	Frontend Frontend Crossmember	Lanxess 2010, Lanxess 2008, ErlingKlingler 2015
7.	Advanced design freedom	7.1	Realise complex geometries	Crossmember Frontend Crossmember Seat shell	Jäschke et al. 2004, Lanxess 2010, ErlingKlingler 2015, Schulte et al. 2015

These potentials represent different areas of actions to consider when one takes multi-material-design into account as a design alternative. Based on the conducted literature review, we derived a preliminary profile of the specific potentials of multi-material-design. This profile is derived from the frequency in which the single potentials are mentioned. The profile presented in Figure 2 highlights that most of the components analysed focus on product related properties and only a few are motivated by process-related improvements. However, the representation of the seven fields as a complete circle points out that there are effects on both classes of potentials. The proposed fields of potentials as well as the given profile address the level of strategic knowledge. On this level, general indications are given and a structured pattern is provided to discuss - in a design team - possible improvements which can be achieved by multi-material-design. On this level, we propose not to act with quantitative criteria but to define core areas for possible improvements.

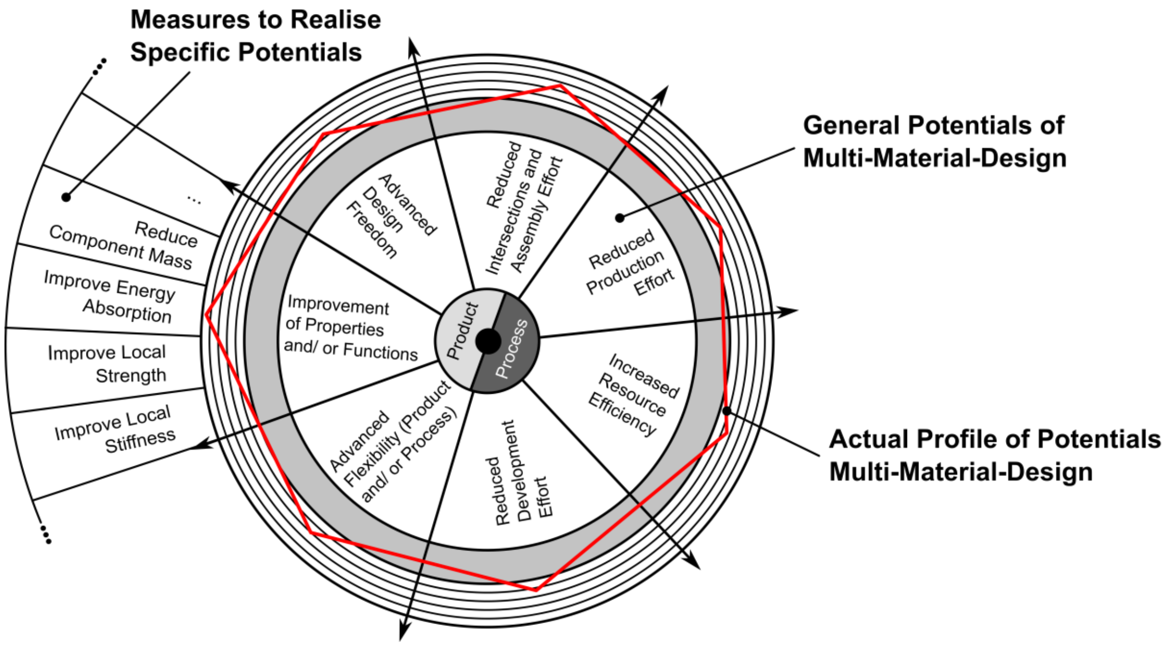

Figure 2. Semi-formal model to structure potentials and measures for multi-material-design

The outer ring of the model points out measures to realise the different potentials. For each potential, we derived more than one measure. Moreover, there are measures addressing more than one field of potentials. For instance, "Improve local stiffness" is a measure clearly assigned to the field "Improve properties and/or functions", whereas "Integration of joint points" is a measure which is assigned to the fields "Advanced design freedom" and "Reduced intersections and assembly effort". Table 2 gives an overview of the defined potentials, the allocated measures and their references. The measures formulated serve as references to realise the proposed potentials by multi-material-design but do not give detailed information for the design itself. However, the increased level of detail and the explicit reference to single product or process properties like mass, stiffness or number of assembly steps support to localise fields of action, for instance based on weak spots of existing products. Therefore, the measures represent problem-situated knowledge and functions as a link between the strategic level (fields of potentials on inner circle) and procedural knowledge provided by the design guidelines.

The proposed model aims at supporting the decision-making in multi-material-design as well as the access to design guidelines. Therefore, it indicates the assignment of general potentials and measures to realise these. The semi-formal character results from the partially not explicit assignment of measures and potentials. However, the model can be understood as a checklist to evaluate whether single measures are suitable for the design task at hand and highlights the broadness the effects of multi-material-design have to the product but also the processes. The following section will introduce the assignment of the introduced measures to design guidelines for multi-material-design.

4 ACCESSING DESIGN GUIDELINES BY MEASURES AND POTENTIALS

In order to support multi-material-design, knowledge on how to design a component is required. This procedural knowledge can be formulated by design guidelines representing common practice of design as well as restrictions, for instance resulting from specific production technologies for multi-material components. Complementary to the model to structure and access strategic and problem-situated knowledge, current research aims at developing a knowledge management system to gather and provide

specific information for the development of components in multi-material-design as well as to enhance the engineers' expertise (Kleemann et al., 2016). This knowledge management system contains design guidelines for multi-material-design derived from the analysis of existing components (see section 2) as well as related fields of research like lightweight design. The design guidelines are formulated based on a literature survey regarding lightweight design, composite design, manufacturing technologies and functional integration. For identifying design guidelines, we analysed textbooks as well as research papers.
As shown in Figure 3, each design guideline is defined by a short title, an explanation, pictures (good and poor example) and reference(s). The simply formulated instructions allow quick access to knowledge (Nehuis et al., 2011). To highlight the design guidelines, two figures are provided, representing unfavourable and favourable designs and providing insights for the design itself. The figures also allow inexperienced designers to quickly understand the principle idea and ease the transfer to the design task at hand (Salustri et al., 2008). The layout of the Knowledge Managements System is shown in Figure 3.

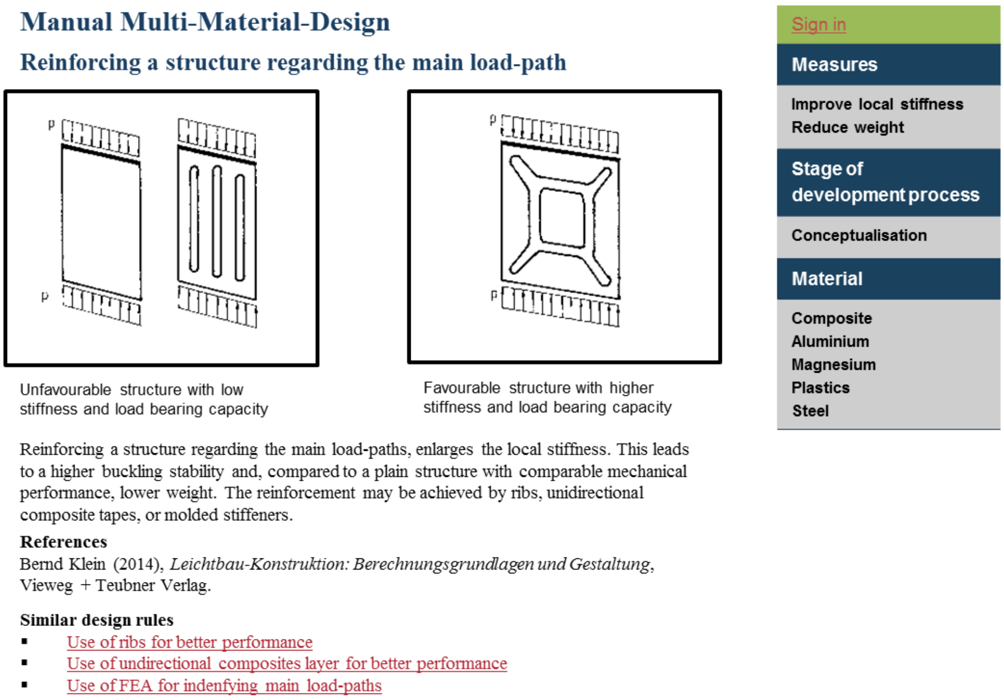

Figure 3. Modified "Manual Multi-Material-Design"

The design guidelines are assigned to a sensible amount of measures, stages of the development process, materials and production technologies. This allows different ways to access the information provided during the design process. Moreover, other design guidelines are suggested which are similar in terms of the assigned measures, stage of the development process, material and/or production technology. The designer is able to browse through the measures mentioned before and, in doing so, achieve a potential of multi-material-design. Additionally, the user can place a request for design guidelines based on key words (e.g. reinforcement, stiffener, demoulding) with an optional filtering based on the potentials and phases of the development process mentioned above.
The link between the semi-formal model of potentials and measures is given by the allocation of design guidelines to the defined measures, see Table 3. For each measure, at least one design guideline is given. This allows an access to the guidelines based on a specific measure and the related potential (top down access). Furthermore, the knowledge management system contains the allocation of potentials and measures to each guideline. This linking allows an understanding of the effect a specific design guideline has with regard to the potentials defined (bottom up analysis).
Table 3 shows an excerpt of measures and related design guidelines. The design guidelines shown are derived from the analysed multi-material-components such as automotive front-ends. Here, the use of injection moulding allows to increase the material efficacy, reduce the number of tools, reduce production steps, reduce logistics and storage, an integration of components and joining elements and to realise complex geometries.

Table 3. Excerpt of measures and assigned design guidelines for multi-material-design

No.	Measure	Design Guideline
1.1	Enlarge local stiffness	Reinforce a structure regarding the main load-paths
1.2	Enlarge local strength	Use of unidirectional composite tapes for better performance
1.3	….	….
2.1	Vary wall thicknesses	Use of composites patches for locally adjusted wall thickness
2.2	Vary material distribution	Use plastics to close surfaces
2.3	….	….

The introduced knowledge management systems contain design guidelines for multi-material-design. The designer is able to browse through the before mentioned measures and potentials and, on the one hand, find suitable design guidelines. On the other hand, the system indicates which potential is affected by the single design guidelines. By now, the implementation is prototypic and available online. The knowledge management system is currently being tested by researchers and graduate students working in the field of automotive lightweight design and multi-material-design.

5 CONCLUSION, DISCUSSION AND FURTHER RESEARCH

The research presented aims at indicating the general potentials of multi-material-design based on serial-parts and pre-serial parts in automotive industry and use these as means to structure and access design knowledge. These potentials are an aggregation of more specific measures, which could be applied during the design process. The measures serve to structure detailed design knowledge given by design guidelines. The identified potentials, measures and design guidelines of multi-material-design have been implemented into a knowledge management system and may allow quick access to suitable design guidelines as well as the effect on guidelines to the different potentials.
The proposed potentials of multi-material-design and the identified measures make no claim to be complete. There are several topics which are not yet included like, for instance, company strategic decisions such as using multi-material-design to demonstrate competitors and customers technology leadership or the capability of innovation. Also, the presented approach does not sufficiently consider costs. A component in multi-material-design is often more expensive compared to monolithic state-of-the-art components from a unit costs point of view. Nevertheless, multi-material-design offers advantages in manufacturing and assembly. Therefore, the designers need to assess the overall costs and analyse whether multi-material-design may amortise over the produced quantities. Furthermore, the hierarchical structure of potentials and measures might not be suitable in general since there are poly-hierarchical interrelations (Roth, 2000) between measures and potentials on the one hand, design guidelines and measures on the other hand. However, the proposed model of the specific potentials and measures provides a useful basis when reasoning about the use of multi-material-design for a specific design task. Moreover, the model helps to structure the knowledge needed for decision-making and realisation on multi-material-design.
The research described within this paper presents a first step towards a holistic method to support multi-material-design in automotive industry. Our further work will focus on two areas. In a first step, will we extend the analysis and definition of potentials and measures in order to assure and refine the ones presented. Moreover, we will perform interviews with technology and design experts in the field of multi-material-design to evaluate the profile of potentials of today's state-of-the-art as well as expected in the future. The second area will focus on the expansion of the design guidelines and the format in which they are provided.

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